

The Quark-Meson Coupling model as a description of dense matter

J. D. Carroll

*Centre for the Subatomic Structure of Matter (CSSM), Department of Physics,
University of Adelaide, SA 5005, Australia*

Abstract. Quantum Hadrodynamics provides a useful framework for investigating dense matter, yet it breaks down easily when strangeness carrying baryons are introduced into the calculations, as the baryon effective masses become negative due to large meson field potentials. The Quark-Meson Coupling model overcomes this issue by incorporating the quark structure of the nucleon, thus allowing for a feedback between the nuclei and the interaction with the meson fields. With the inclusion of this feature, QMC provides a successful description of finite nuclei and nuclear matter. We present the latest parameterization of QMC and discuss the predictions for dense nuclear matter and ‘neutron’ stars.

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1. INTRODUCTION

The Quark-Meson Coupling model (QMC) [1, 2, 3, 4, 5, 6] has proven to be an extremely useful tool for calculating the properties of matter at various density scales—from finite nuclei [3] to neutron stars [4]—where the global properties of these objects can be accurately predicted and compared with experiment in an effort to refine the model parameters.

While other models for these systems have been investigated by many others [7, 8, 9], QMC uniquely distinguishes itself as a relativistic description at the quark level, constrained only via the quark-structure of baryons and a few baryon-meson coupling constants (for a thorough description, see [5]), fit to experimental data.

2. QMC

In order to calculate the properties of finite nuclei (including hypernuclei) and neutron stars, we require a parameterization of the baryon effective masses, M_B^* which is determined self-consistently using the QMC model, and which has a quadratic dependence on the scalar mean-field. This quadratic dependence is a distinguishing feature of QMC as compared to Quantum Hadrodynamics (QHD) which models a linear dependence of the effective mass on the scalar mean-field [7]; a feature which leads to negative effective masses at large baryon densities.

With a parameterization of M_B^* , we are able to calculate the properties of infinite nuclear matter, in which baryons are in beta-equilibrium with leptons, including attractive and repulsive potential contributions from scalar σ , and vector ω and ρ mesons. For example, using the parameterization found in Ref. [2] we calculate the properties of infinite matter under the constraints of global charge neutrality and conserved baryon density, as shown in Figure (1)(a). The couplings constants g_σ , $g_{\omega B}$, and g_ρ of the baryons B to the various mesons are determined by the standard procedure of fitting the properties of saturated nuclear matter.

We note that the fractional density of Σ^- baryons decreases above a certain density, while that of the remaining baryons tend toward a common value at large densities. We also note that the threshold density for Ξ hyperons to appear is well below that of the Σ^0 and Σ^+ hyperons.

The parameterization of the baryon effective masses has been refined over time to better reflect the properties of hypernuclei. Most recently in particular in 2008, by the self-consistent inclusion of one-gluon-exchange hyperfine terms that lead to the N - Δ and Σ - Λ mass splittings in free-space. A consequence of this is that the Σ hypernuclei are unbound in this model, which is consistent with the lack of evidence from the experimental searches for these. The parameterization is given in terms of the scalar mean-field $\langle \sigma \rangle$ by

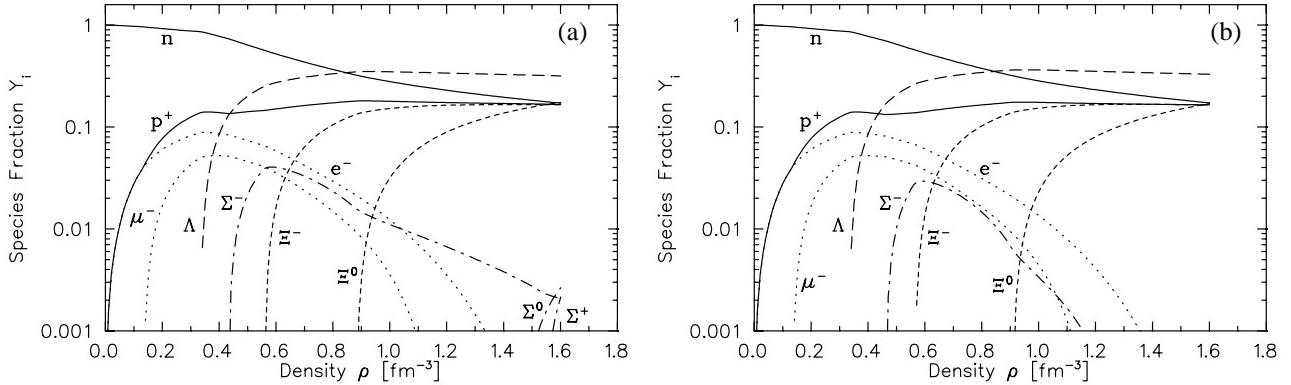


FIGURE 1. Species fractions Y_i for hyperonic QMC hadronic matter calculated using the 2007 ((a), from [2]), and 2008 ((b), from [3]) parameterizations of the effective masses. Note the suppression of the Σ baryon densities predicted using the 2008 parameterization.

$$\begin{aligned}
M_N^* &= M_N - g_{\sigma N} \langle \sigma \rangle \\
&\quad + \left[0.002143 + 0.10562 R_N^{\text{free}} - 0.01791 (R_N^{\text{free}})^2 \right] (g_{\sigma N} \langle \sigma \rangle)^2, \\
M_\Lambda^* &= M_\Lambda - \left[0.6672 + 0.04638 R_N^{\text{free}} - 0.0022 (R_N^{\text{free}})^2 \right] g_{\sigma N} \langle \sigma \rangle \\
&\quad + \left[0.00146 + 0.0691 R_N^{\text{free}} - 0.00862 (R_N^{\text{free}})^2 \right] (g_{\sigma N} \langle \sigma \rangle)^2, \\
M_\Sigma^* &= M_\Sigma - \left[0.6653 - 0.08244 R_N^{\text{free}} + 0.00193 (R_N^{\text{free}})^2 \right] g_{\sigma N} \langle \sigma \rangle \\
&\quad + \left[0.00064 + 0.07869 R_N^{\text{free}} - 0.0179 (R_N^{\text{free}})^2 \right] (g_{\sigma N} \langle \sigma \rangle)^2, \\
M_\Xi^* &= M_\Xi - \left[0.3331 + 0.00985 R_N^{\text{free}} - 0.00287 (R_N^{\text{free}})^2 \right] g_{\sigma N} \langle \sigma \rangle \\
&\quad + \left[-0.0032 + 0.0388 R_N^{\text{free}} - 0.0054 (R_N^{\text{free}})^2 \right] (g_{\sigma N} \langle \sigma \rangle)^2,
\end{aligned} \tag{1}$$

where the value $R_N^{\text{free}} = 0.8$ fm is used (and the dependence on this value has been investigated and found to be small in Ref. [10]).

The relative densities of baryons and leptons in beta-equilibrium for the case of infinite nuclear matter for this new (2008) parameterization are shown in Figure (1)(b). We note that the most striking difference in comparison to the calculation using the 2007 parameterization—which does parameterize the additional hyperfine interactions—is that the contribution of the Σ hyperons has been reduced.

3. NEUTRON STARS

Calculating the mass and radius of a neutron star modelled with QMC involves solving the Tolman-Oppenheimer-Volkoff (TOV) equation

$$\frac{dP}{dR} = -\frac{G(P+\mathcal{E})(M(R)+4\pi R^3 P)}{R(R-2GM(R))}, \tag{2}$$

for a given Equation of State (EoS), in this case an EoS calculated using QMC (see Refs. [5, 6] for details). The TOV solutions for a range of central densities are shown in Figure (2) for the 2007 and 2008 parameterizations of the effective masses. We note that the choice of parameterization does not significantly affect the solutions to the TOV equation.

We further note that the maximum predicted stellar mass calculated using either parameterization of the effective baryon mass does not exceed $1.57 M_\odot$, which can be attributed to the softness of the EoS due to the large number of

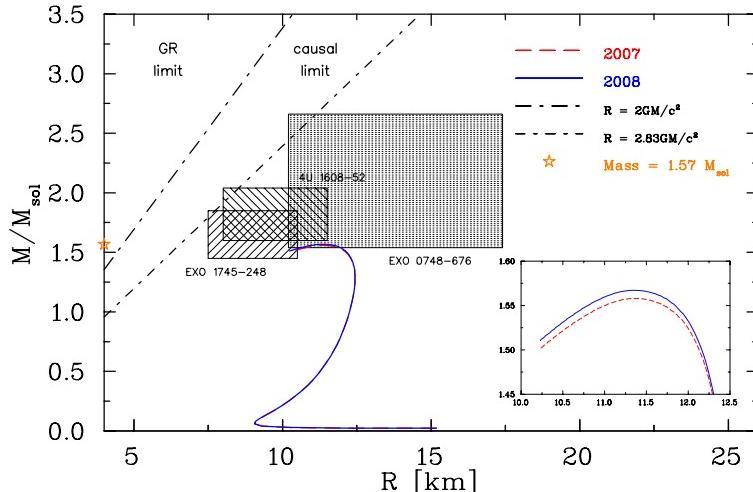


FIGURE 2. (Color online) Predicted total stellar mass and radius solutions of the TOV equation for hyperonic QMC using the 2007 and 2008 parameterizations of the effective mass. Also shown are the data points from Refs. [11] (EXO 0748-676), [12] (EXO 1745-248), and [13] (4U 1608-52), as well as the maximum mass predicted from either data set (star). Inset: Separation of the two data sets at the maximum stellar mass.

baryons present—at large densities, at least six of the octet baryons possess nontrivial fractional densities. This is in conflict with the observational evidence of larger mass neutron stars, though we caution using a direct comparison between these predictions (which correspond to static, spherically symmetric, non-rotating objects) and physical neutron stars which may not satisfy such approximations.

Future work will include investigating the effects of rotation on the stellar solutions, and inclusion of Fock (exchange) terms to the baryon self-energies, in an effort to increase the accuracy of our description of dense nuclear matter.

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